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NASA CASE NO. NPO-17,022-CU
PRINT FIG. 1

NOTICE

16 P.

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NRO-JPL

{NASA-Case-NPO-17022-1-CU} SAMPLE
LEVITATION AND MELT IN MICROGRAVITY Patent
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AWARDS ABSTRACT

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Inventor: Philip I. Moynihan April 30, 1987

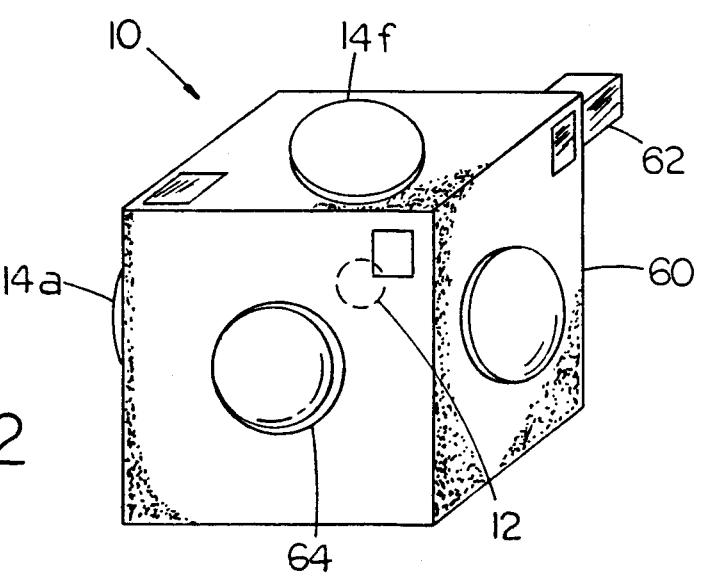
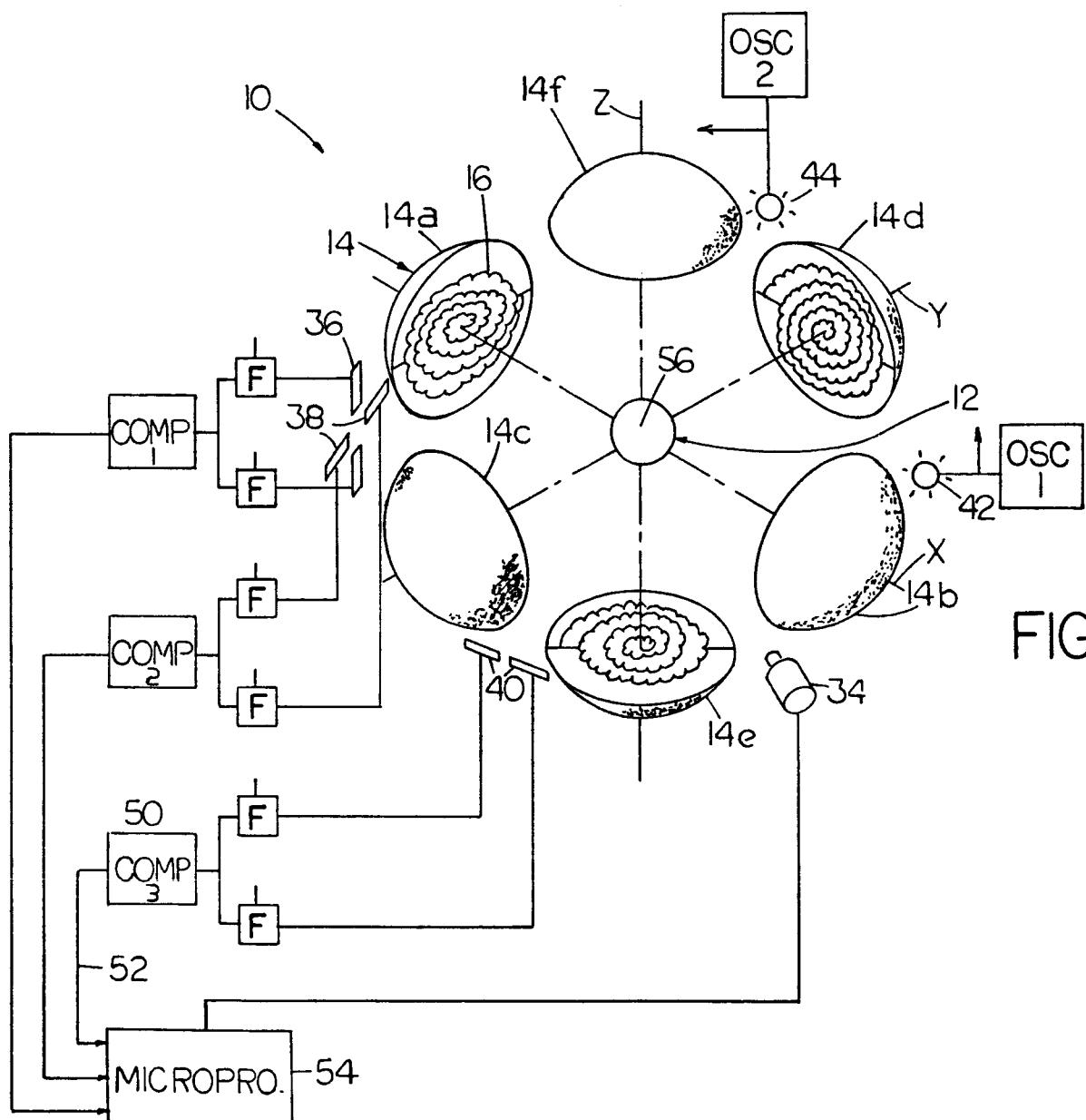
SAMPLE LEVITATION AND MELT IN MICROGRAVITY

The object of the invention is to provide a system for use on a space vehicle subjected to microgravity to levitate, or hold, a molten mass in position without contact with any container, and to heat the mass.

The mass or object 12 (Fig. 1) is gently urged in any desired direction by the radiation pressure of infrared light emitted by infrared sources 14a-14f. To urge the object away from one source 16a, the infrared output of that source is increased, while the output of the opposite source 14b is decreased. The infrared radiation heats the object to raise its temperature to the melting point or to maintain it thereat, while also levitating the object. Calculations show that the radiation pressure from available heated filament infrared sources such as shown at 14 in Fig. 1 can apply sufficient force on an object to counter a microgravity of 10^{-5} . This force is the amount required to hold an object in position on a spacecraft orbiting the earth at an altitude of 100 miles, which is subject to deceleration due to the drag of rarified air at that altitude that results in a microgravity of about $10^{-6}G$ to $10^{-5}G$.

A major novelty is the use of electromagnetic radiation, especially in the infrared, to levitate an object as well as to heat it.

Serial No.	066,450	
Filing Date	6/26/87	
Contract No.	NAS7-918	
Contractor	Caltech/JPL	
Pasadena (City)	CA. (State)	91109 (Zip)



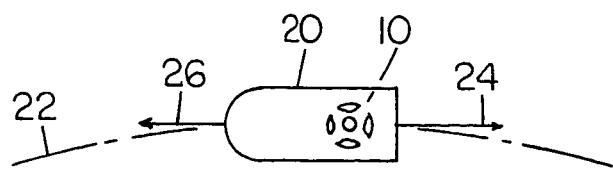


FIG. 3

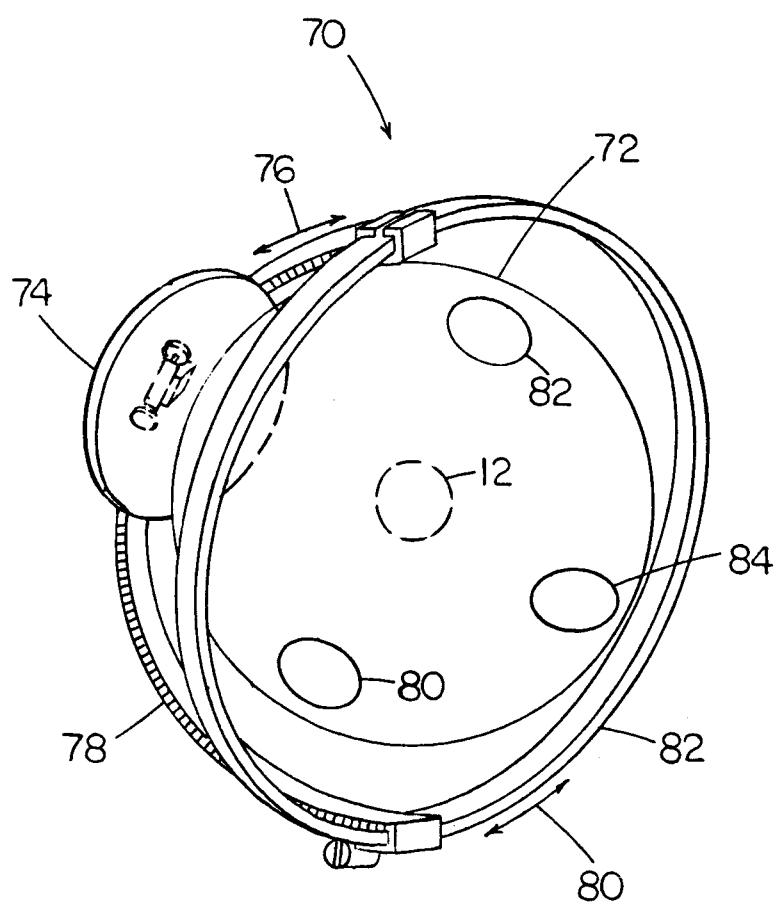


FIG. 4

JPL Case No. 17022
NASA Case No. NPO-17022-1-CU

Serial No.	066,450	
Filing Date	6/26/87	
Contract No.	NAS7-918	
1-	86/299	
Contractor	Caltech/JPL	
Pasadena	CA.	91109
(City)	(State)	Patent (Zip)

SAMPLE LEVITATION AND MELT IN MICROGRAVITY

ORIGIN OF THE INVENTION:

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 5 202) in which the Contractor has elected not to retain title.

BACKGROUND OF THE INVENTION:

Investigations of high melting temperature materials in an ultra-high purity state is best 10 conducted by maintaining a material sample in a molten state while it is isolated from potential sources of contamination. A sample can be levitated, or held in place, in a microgravity environment such as exists in an orbiting space vehicle, by several techniques. One 15 levitation technique involves the application of an acoustic standing wave within a container, but this requires the sample to be immersed in a gaseous medium which could contaminate it, and also results in high-frequency disturbances to the sample from the 20 high-frequency acoustic energy. In addition, it is very difficult to heat the levitated sample. Another technique involves the directing of electron or ion beams at the sample, but this can result in the injection of the electrons or ions into the sample which 25 can affect its characteristics. A system which could levitate a molten object to avoid its contact with the walls of a solid container, which minimized or avoided contact of the molten object with even subatomic particles that have masses, while minimizing 30 disturbances of the levitated object, would be of

considerable value. Any such system which could maintain the object at an elevated temperature while levitating it, using relatively low-cost devices, would be of considerable value.

5 SUMMARY OF THE INVENTION:

In accordance with one embodiment of the present invention, a method and apparatus are provided for levitating an object in a microgravity environment while maintaining it at an elevated temperature, and while 10 minimizing contamination of the object. At least one source of electromagnetic radiation is located on a facility, such as a spacecraft, in a microgravity environment, and the source is positioned to direct electromagnetic radiation at the object. The 15 electromagnetic radiation (generally infrared radiation of about 10^{-6} meters wavelength) produces a mechanical pressure, and the vector sum of the radiation pressure opposes excessive drift of the object, to counter movement of the object that would otherwise occur in the 20 microgravity environment. The net sum of electromagnetic radiation directed at the object is preferably sufficient to maintain the object in a molten state.

Where the space vehicle on which the object is 25 located is in Earth orbit, the vector sum of electromagnetic radiation is opposite the velocity of the space vehicle. Thus, drift of the object due to microdeceleration of the space vehicle caused by air resistance is avoided. In one system, a group of 30 electromagnetic radiation sources are positioned along three mutually perpendicular axes, and the relative power levels at which the sources are energized is varied to control the net vector of radiation pressure. In another system, at least one of the radiation sources 35 is movable.

The novel features of the invention are set forth with particularity in the appended claims. The invention will be best understood from the following description when read in conjunction with the 5 accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS:

Fig. 1 is a perspective and block diagram view showing the basic elements of a levitation system constructed in accordance with one embodiment of the 10 present invention.

Fig. 2 is a perspective view of the system of Fig. 1 showing a container surrounding the levitated object.

Fig. 3 is a representational view of a 15 spacecraft in orbit around the Earth, and on which the system of Fig. 1 is mounted.

Fig. 4 is a partial perspective view of a levitation system constructed in accordance with another embodiment of the invention.

20 DESCRIPTION OF THE PREFERRED EMBODIMENTS:

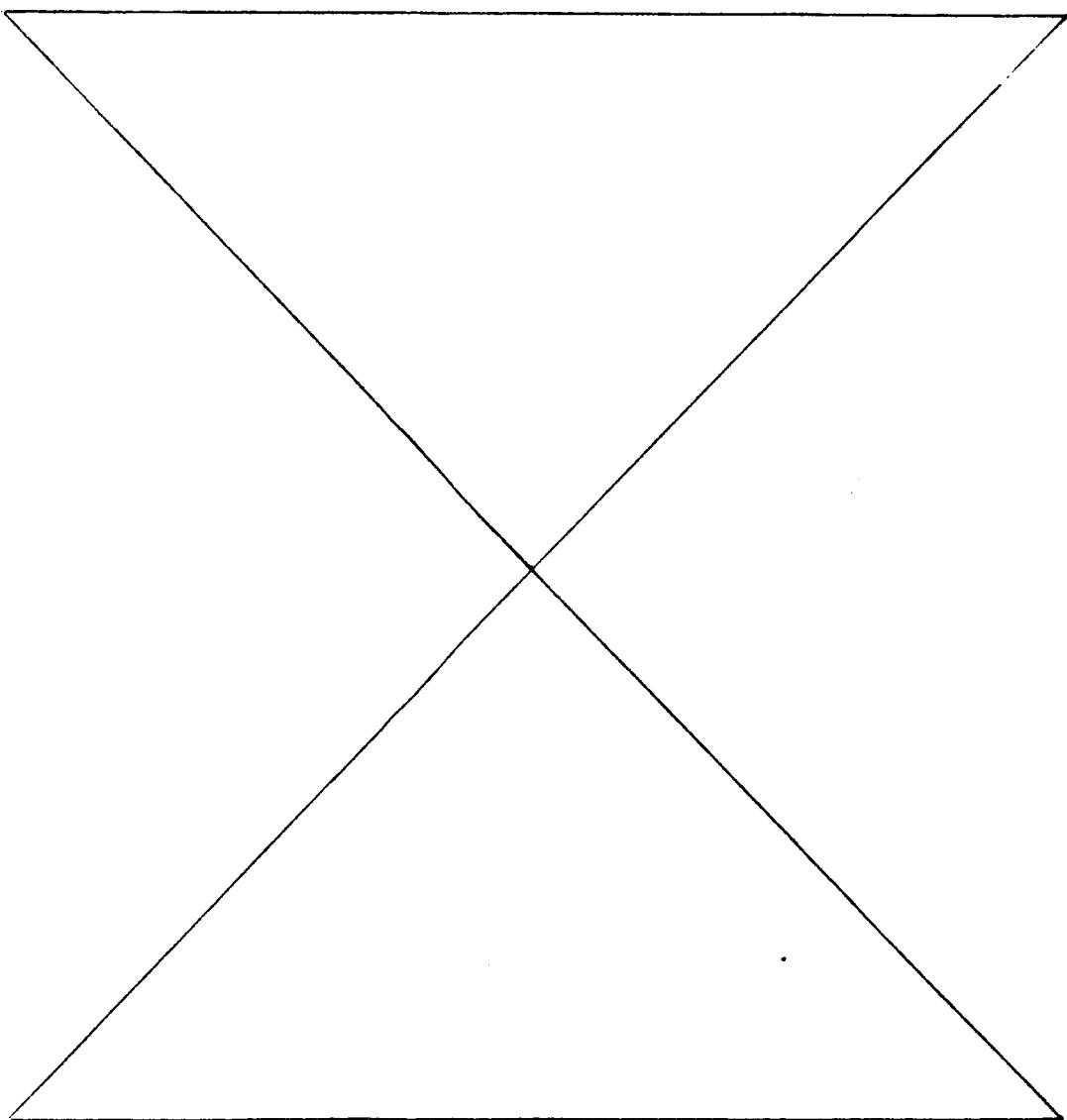
Fig. 1 illustrates a system 10 which can be mounted on a space vehicle where there is a microgravity environment, for heating an object 12 and for levitating the object to hold it approximately in a desired 25 position relative to the spacecraft. The system includes several sources 14 of electromagnetic radiation, which are spaced about the object to direct the radiation at the object from different directions. The system of Fig. 1 includes six sources 14a-14e, with 30 pairs of such sources located along each of three mutually perpendicular axes X, Y, and Z. Each of the sources 14 includes a coiled filament 16 which can carry current to become heated and emit electromagnetic radiation, primarily in the infrared spectrum. The

radiation emissions serve to heat the object 12 to a molten state and to maintain it in that state for an extended period of time. The radiation emitted by the sources also apply a radiation pressure to the object 5 which can be sufficient to hold the object in position relative to the sources and to a spacecraft on which the sources are mounted.

There are many applications in material science where it is desirable to heat an object to its molten 10 temperature and maintain it thereat without the object coming in contact with any material (sometimes even gases). Such applications are not only to identify new materials and processing techniques, as to obtain precursors for optical fiber production, but also to 15 study fundamental physical and chemical phenomena. For example, it is desirable to investigate homogenous and heterogeneous nucleation and crystallization of glasses. On Earth, glasses tend to crystallize heterogeneously, with initiation on the container 20 walls. Also, impurities introduced from the container may introduce crystal nucleation rates even for glasses nucleating in the bulk, all of which renders study very difficult on Earth. A system for heating the glasses 25 while levitating them in a vacuum can enhance such studies.

When the processing system 10 lies on a space vehicle such as shown at 20 in Fig. 3, which is in an orbit 22 around the Earth 24, the system is in a microgravity environment. The system is subjected to 30 disturbances, such as when an astronaut moves on the vehicle, but such disturbances generally cause only a temporary movement of the object, with the return of the object to its initial position at the end of the disturbance. However, the space vehicle is subject to a 35 constant deceleration in a direction 24 opposite to its orbital velocity. Such deceleration is due to drag of

the space vehicle from rarified air. For example, a space vehicle in an orbit 100 miles above the Earth experiences deceleration resulting in a microgravity of about $10^{-6}G$ to $10^{-5}G$ (where 1G is gravity on the Earth's surface). A small but non-negligible force must be applied to the levitated object to prevent it from slowly accelerating in the direction 26 of the microgravity.



A major question in the use of pressure generated by electromagnetic radiation is whether sufficient pressure can be applied to actually levitate an object under typical conditions that would be 5 encountered. The following sets forth formulas for calculating the force of electromagnetic radiation produced on an object by a radiation source, and is followed by a specific example. The force F (in dynes) on an object produced by electromagnetic radiation 10 thereon is given by:

$$F = pA_2 \text{ dynes} \quad \text{Eq. 1}$$

Where A_2 is the area in cm^2 of the object exposed to the radiation and p is the flux or radiation pressure per unit area in dynes per cm^2 . The 15 radiation pressure p is given by:

$$p = \frac{4}{3c} \frac{q_{1-2}}{A_1} \times 10^7 \times A_2 \text{ dynes/cm}^2 \quad \text{Eq. 2}$$

Where A_1 is the area in cm^2 of the source of electromagnetic radiation facing the object, c is the speed of light which equals $2.998 \times 10^{10} \text{ cm/sec}$, and 20 q_{1-2} is the radiation exchange in watts between the two objects. The radiation exchange q_{1-2} between two "gray" objects can be expressed as:

$$q_{1-2} = \frac{1}{\frac{1}{A_2} \left(\frac{1}{e_1} - 1 \right) + \frac{1}{A_2} \left(\frac{1}{e_2} - 1 \right) + \frac{1}{A_1 \bar{F}_{1-2}}} s(T_1^4 - T_2^4) \quad \text{Eq. 3}$$

Where e_1 and e_2 are the emissivities of the 25 source and the object, \bar{F}_{1-2} is the view factor representing how much of the angle of view of the source is taken up by the object and vice versa, s is the Stefan-Boltzman constant which equals $5.667 \times 10^{-12} \text{ w/cm}^2 \text{K}^4$, and T_1 and T_2 represent the 30 temperatures in degrees Kelvin of the source and object, respectively.

In one example, a glass material sample of 1 cm diameter ($A_2 = 0.785\text{cm}^2$) is located 0.635 cm (one-quarter inch) from the heat source. The sample has a density d of 2.72 gm/cm^3 , and therefore has a specific density d_s of $2,670 \text{ dynes/cm}^2$. The weight W of the sample in a 10^{-5}g field is:

$$W = d_s V \frac{g}{g_0} = 2,670 \times \frac{\pi}{6} D^3 \times 10^{-5} = 0.014 \text{ dynes} \quad \text{Eq. 4}$$

Thus, a radiation force of at least 0.014 dynes must be exerted opposite to the microgravity field to prevent sample movement relative to the spacecraft.

Continuing with the above example, it may be assumed that a tungsten filament heat source is used with the tungsten coiled to 1 cm diameter ($A_1 = 0.785\text{cm}$). The tungsten filament is heated to a temperature $T = 6,000^\circ \text{ F} = 3588^\circ \text{K}$. The emissivity of the sample is assumed to be 0.30, while the emissivity of the heated tungsten filament is assumed to be 0.35. The view factor of the sample and heat source of the above dimensions and separation is given by the following (r_1 , r_2 , and L are respectively the radii of the heat source and of the sample, and their separation):

$$\begin{aligned} \bar{F}_{1-2} &= \frac{1}{2r_1^2} [L^2 + r_1^2 + r_2^2 - \sqrt{(L^2 + r_1^2 + r_2^2) - 4r_1^2 r_2^2}] = \\ &= \frac{1}{2(.5)^2} [0.635^2 + .5^2 + .5^2 - \sqrt{(0.635 + .5^2 + .5^2)^2 - 4(.5)^2 (.5)^2}] \\ &= 0.302 \quad \text{Eq. 5} \end{aligned}$$

Using the above numbers in equation 3, the initial heat exchange of the source and sample (the

sample is assumed to be at 293°K) equals:

$$q_{1-2} = \frac{1}{\frac{1}{.785} \left(\frac{1}{.35} - 1 \right) + \frac{1}{.785} \left(\frac{1}{.3} - 1 \right) + \frac{1}{.785} (.302)} \times (5.667 \times 10^{-12}) (3,588^4 - 293^4) = 98.7w \quad \text{Eq. 6}$$

Using the above numbers in equations 1 and 2,
5 the force imparted on the sample by the radiation pressure is:

$$F = pA_2 = \frac{4}{3(3 \times 10^{10})} \frac{98.7}{.785} \times 10^7 \times .785 = 0.044 \text{ dynes} \quad \text{Eq. 7}$$

Thus, when the sample is at room temperature,
10 the radiation pressure of 0.044 dynes is greater than the "weight" of 0.014 dynes of the sample in a 10^{-5} g microgravity environment. It may be noted that the above example assumes the radiation source is omnidirectional, rather than the radiation being concentrated at the sample which produces greater
15 heating and a greater radiation pressure. When the sample reaches a desired equilibrium temperature such as 2,000°C (2,273°K) the heat exchange between the source and sample becomes:

$$q_{1-2} = 82.80 \text{ watts}$$

20 Which results in a radiation force of:

$$F = 0.037 \text{ dynes}$$

Thus, the force on the sample at equilibrium temperature of 0.037 dynes, exceeds the 0.014 dyne weight of the sample in this example. The radiation pressure is dominated by the source temperature, and does not vary significantly as the sample temperature increases from ambient to 2,000°C. In the above example, an estimate of the time required for the sample

to reach 2,000°C is about 15 minutes. Cold sources, such as cooled plates at the positions of sources 14b-14f in Fig. 1, can be used to allow the sample to cool while radiation from a hot source 14a maintains 5 sample position. Alternately, the intensities of the radiation sources can be altered. The above example serves to demonstrate that a feasible radiation source for heating a feasible sample to be processed, can apply sufficient force through electromagnetic radiation 10 pressure to hold the sample against microgravity forces that can be encountered, and especially the microgravity resulting from drag on a space vehicle orbiting the Earth.

Referring again to Fig. 1, the system includes 15 an energizing circuit 30 having six outputs 32, each connected to a different one of the sources 14a-14f to energize it (a ground return is not shown). The average energization of the six sources is determined by the difference between the actual sample temperature as 20 determined by a sensor 34 and the desired sample temperature. The position of the sample is sensed by three pairs of light sensors 36-40. Each pair of sensors senses light from one of two light generators 42, 44 to sense movement of the object in any one of 25 three dimensions. The outputs of each pair of sensors such as 40a, 40b is passed through a separate filter 46 to a comparator 50 which generates an output on line 52 proportional to the difference in outputs of the two sensors, which indicates object movement. The outputs 30 of the three comparators are delivered to a microprocessor 54 which controls the relative energizations of the six radiation sources by circuit 30. If the object moves away from a desired initial position 56, and that movement persists long enough 35 (e.g., 5 seconds) to indicate a continuous drift rather than a temporary disturbance, the microprocessor

controls the energizing circuit 30 to increase current to those sources towards which the object is moving and to decrease the current to the sources away from which the object is moving.

5 Fig. 2 illustrates additional details of the system 10, showing a container 60 surrounding the object 12, and with a conduit 62 leading from the inside of the container to the outside of the spacecraft, where there is a very low-pressure vacuum, which is much less than
10 one-thousandth atmospheric pressure. Where desired, it is possible to maintain an inert gas within the chamber. A quartz or other acceptable window 64 lies between the filament of each source of electromagnetic radiation and the object, to avoid the passage of most
15 particles (except photons). Where a filament is used which does not outgas significantly, such a window barrier can be eliminated.

It may be noted that where a known microgravity force exists in a known direction, such as along the
20 orbital velocity of a space vehicle, the source or sources lying in the direction to which the object is urged by the microgravity can be constantly energized at a sufficiently higher level than opposite sensors to counteract the sustained microgravity. Then, an
25 occasional change in energization pattern occurs primarily when unpredicted microgravity sources are present.

Fig. 4 illustrates another system 70 for heating and levitating an object 12 within a container 72, which
30 is especially useful where there is a constant microgravity present such as in an orbiting spacecraft. A main electromagnetic source 74 is movable in directions 76 on a first guide 78, while the first guide is movable in directions 80' on a second guide 82'.
35 This allows the source 74 to be moved relative to the spacecraft about the levitated object. The main source

74 is located on a side of the object towards which microgravity tends to move the object. If the object wanders, the position of the source 74 can be altered, as can its level of radiation output. Additional 5 secondary sources 80-84 serve to heat the object more uniformly and enable the application of radiation pressure opposite to the usual direction.

Thus, the invention provides a method and apparatus for heating an object and levitating it. The 10 system includes sources of electromagnetic radiation, which are devoid of particle radiation, for heating the object and for applying radiation pressure that levitates the object, while avoiding contamination of the object. The above analysis shows that in a 15 practical system the radiation pressure is sufficient to levitate an object under microgravity forces that are likely to be encountered in a space vehicle during sample processing.

Although particular embodiments of the invention 20 have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art, and consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

SAMPLE LEVITATION AND MELT IN MICROGRAVITY

ABSTRACT OF THE DISCLOSURE

A system is described for maintaining a sample material in a molten state and away from the walls of a container in a microgravity environment, as in a space vehicle. A plurality of sources of electromagnetic radiation, such as of an infrared wavelength, are spaced about the object, with the total net electromagnetic radiation applied to the object being sufficient to maintain it in a molten state, and with the vector sum of the applied radiation being in a direction to maintain the sample close to a predetermined location away from the walls of a container surrounding the sample. For a processing system in a space vehicle that orbits the Earth, the net radiation vector is opposite the velocity of the orbiting vehicle.